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ANALYSIS OF THE MECHANICAL BEHAVIOR OF ADHESIVELY BONDED COMPOSITE JOINTS

FINAL REPORT

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This report summarizes research on characterizing a composite polymeric adherend material and studying, experimentally and theoretically, its reaction in one adhesive joint configuration. The particular material investigated is a continuous-fiber graphite/epoxy composite material with a rubber-toughened matrix. The composite is nonlinear and viscoelastic at room temperature. A constitutive equation is developed to account for this behavior, and it is then used in a finite element analysis of an adhesive joint. Experimental verifications of the constitutive model and adhesive joint are made.

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SUMMARY OF WORK ACCOMPLISHED

In order to understand the mechanical state of an adhesively bonded joint, it is necessary to consider the properties of the adhesive and adherend materials, their structural configuration, and their operational environment. The present research involved characterizing a composite polymeric adherend material and studying experimentally and theoretically its response in an adhesive joint. The particular material investigated is a nonlinear and viscoelastic continuous-fiber graphite/epoxy with a rubber-toughened matrix. The objective of the study was to develop a mathematical model to account for this behavior and apply it to the adhesive joint using the finite element method. Experimental validation of the material model and adhesive joint was made.

The adherend material was characterized using two methods, one using a nonlinear viscoelasticity theory and one using a time-dependent potential theory. The second method was based on a complementary work-potential which accounted for changes in the microstructure with a one parameter flow rule. This material was then used to study the effects of adherend creep in a single-lap joint bonded assembly. The single-lap joint configuration was chosen because of the particular state of stress it caused in the adherends. Due to the eccentricity in load path, large stresses were induced in the adherends which, with the tough resin composite, caused an appreciable amount of creep. Its ease in fabrication was an added advantage. Composite adherends were constructed of the 0° unidirectional and angle-ply layups. The 0° layup provided an examination of the effects of composite adherend manufacture, as well as small three-dimensionality and the absence of significant adherend viscoelasticity. The angle-ply demonstrated the effects of adherend creep and large three-dimensionality. Response due to a time-

dependent adherend material was investigated experimentally with constant load rate testing to failure. Two constant load rates were used. Changes with rate were observed in adhesive joint failure patterns and surface strains. An aluminum adherend system was also used to validate experimental and theoretical procedures.

The finite element method was then used to predict the strains in the legs and on the outer surface of the joint. A commercially available finite element program ABAQUS (Hibbitt, Karlsson, and Sorensen, Version 4.5) was used for the mechanical analysis, with the material characterization provided through a user-subroutine. An incremental constitutive model was developed and added to the finite element code. A time-dependent work-potential model was used for the composite adherend material in the finite element analyses. Strains on the outer surface were then predicted accounting for material and geometric nonlinearities. Linear solutions were also calculated. Based on this research, the following conclusions were drawn:

1. Material characterization with Schapery's nonlinear single-integral theory was unsuccessful because it does not account for changes in the microstructure (damage) seen in the material. Attempts at mechanically conditioning samples to characterize the material in a stable state of damage showed that there was an additional amount of strain present in the nonlinear range which did not follow the viscoelastic theory. For linear data, this method of characterization was useful. A power law time-dependence was seen to be common to all layups tested. Principal compliances determined from the unidirectional samples were used to predict the linear response of the angle-ply compliance.

2. Schapery's work-potential theory was seen to better describe the experimental axial strain response of the rubber-toughened graphite epoxy. A

one parameter flow rule was used to characterize the nonlinear response of the material. Unlike a similar plasticity based method on unidirectional laminae, the method developed here accounts for nonproportional loading of plys in the angle-ply laminate. Upon determining the work-potential, this theory was used to predict the Poisson's ratio of the angle-ply for comparison with that measured experimentally. The agreement between theory and experiment was quite good, giving an independent check of the potential theory's predictability.

3. With all three adherend systems studied, geometric nonlinearity was demonstrated at all strain reading locations except that at the center of the overlap. Material properties of the angle-ply adherend system caused the center of the overlap strain to be nonlinear as well. Results from the aluminum adherend assembly showed that little, if any, viscoelastic behavior was present due to the adhesive material. Strain data from the 0° adherend system compared well qualitatively with the aluminum joint strain readings. Failure of both systems was always in the adhesive. Rate effects of the graphite/epoxy were demonstrated with the angle-ply adherend assembly. Fracture of the angle-ply systems always occurred in the overlap region; fracture occurred in the adhesive for the slow rate and in the adherend for the fast rate, possibly due to a redistribution in strain over the bond area with time.

4. Finite element predictions of the three adherend systems using linear material properties validated that geometric nonlinearities must be accounted for in order to predict surface strains of the single-lap joint. Predictions of the aluminum assembly using linear isotropic material models for the adherend and adhesive material and geometrically nonlinear finite elements showed excellent correlation with experimentally measured surface strains.

Predictions of the 0° adherend system using a similar analysis were equally satisfactory. Predictions of the angle-ply adherend system's surface strains using a linear material model, either elastic or viscoelastic, with geometrically nonlinear finite elements were quantitatively correct only for the small strain range at three of the four gage locations monitored. Those readings at the edge of the overlap were ill-predicted for the entire range of loading, later attributed to the effect of adhesive spew fillets. Qualitatively, these methods did predict the overall trend of experimental data.

5. Addition of the nonlinear work-potential theory to describe the nonlinear material behavior of the graphite/epoxy adherend material greatly improved the quantitative predictability of the finite element method for the angle-ply adherend case. The quasi-elastic method accounted for the creep or rate-dependence of adherend strains, but underpredicted strains in the slow rate test due to the differences in age and environment seen by the adherend material and characterization samples. Predictions of the fast rate data, the less time-dependent of the two rates, were quite good in the outer adherend surface over the entire range of loading. The inclusion of the spew fillets was found necessary to predict strain readings at the edge of the overlap. These results with the spew fillets correctly predicted experimental data in the initial stages of loading. The model without the fillets was best in the final stages of loading; this could be indicative of the failure of the lap joint since fracture begins at the fillets. Once this area has cracked, the straight-edge finite element mesh without the fillets more correctly modelled the experimental behavior. Strain readings at the center of the overlap were improved in the nonlinear range, but still not representative of those measured experimentally, probably due to progressive failure of the fillets

and three-dimensional effects.

Technical Report: L.A. Mignery, "Viscoelastic Adherend Effects in Adhesively Bonded Composite-to-Composite Joints," Ph.D. Dissertation, Aerospace Engineering, Texas A&M University, December 1988 (Completed August 1988). Texas A&M Report No. MM 5558-88-18.

Publication: L.A. Mignery and R.A. Schapery, "Effect of Adherend Creep on Bonded Composite Joints," In Proc. of the Joint ASME/SES Applied Mechanics and Engineering Science Conference, Berkeley, AMD-Vol. 92, 161-168, June 1988.

Note: Abstracts of these two documents are given on the succeeding pages.

VISCOELASTIC ADHEREND EFFECTS IN ADHESIVELY BONDED COMPOSITE-TO-COMPOSITE JOINTS

PH.D. Dissertation by L.A. Mignery

ABSTRACT

A complex state of stress is present in adhesive joints. With composite adherends, this can cause a considerable amount of creep even in the absence of an extreme operational environment. The present research is centered around characterizing a composite polymeric adherend material and studying, experimentally and theoretically, its reaction in one adhesive joint configuration. The particular material investigated is a fibrous graphite/epoxy composite material with rubber-toughened matrix. The composite is nonlinear and viscoelastic at room temperature. The objective of the study is to develop a constitutive equation to account for this behavior and to use it in a finite element analysis of an adhesive joint. Experimental verifications of the constitutive model and adhesive joint are made.

The graphite/epoxy composite is characterized using a viscoelastic model and a work-potential model. Unlike the viscoelastic model, the work-potential model accounts for changes in the microstructure, or damage, as well as viscoelasticity. The quasi-elastic method, in which the actual deformation behavior is approximated by a time-dependent elastic behavior, is used in the second characterization to account for the time dependence of the material. Parameters necessary for each model are determined from creep/recovery and constant load rate data. Single-lap joints made of the same material and a brittle adhesive are then tested at two different load rates to failure. A brittle adhesive is used to isolate most of the viscoelastic response in the adherend material. Strains on the outer surface of the joint are recorded as

well as changes in failure patterns with load rate. A commercially available finite element program is used to analyze the strains on the outer boundary. This program is augmented with an incremental constitutive law using the experimentally determined work-potential model and the quasi-elastic method to account for the nonlinearity and viscoelasticity of the adherend material.

EFFECT OF ADHEREND CREEP ON BONDED COMPOSITE JOINTS*

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ABSTRACT

An experimental and theoretical investigation is presented on the effect of adherend creep on bonded joints between laminates of a graphite/epoxy composite with rubber-toughened resin; for comparison, aluminum adherends were also used. Single-lap joints, using brittle epoxy adhesive to avoid significant time-effects in the bond layer, were tested under two constant load rates to failure. Axial strains were measured at several locations on the outer surface of the adherends and compared to strains from linear and nonlinear finite element analyses.

*Published in ASME AMD-Vol. 92, June 1988.